ON LIGHT AND ILLUMINATION.

By Ernst Gundlach.

One of the greatest evils with which microscopic observation has yet to contend, is, no doubt, the fact that the objects to be examined have to undergo a more or less difficult operation to make them accessible to observation ; and one of the first steps of this operation is to make them transparent, so that the light, coming from the illuminating mirror, may pass right through the object, thus exhibiting its inner structure. It must be admitted that this last is a specially useful peculiarity of microscopic vision, aside from the advantage of amplification, for it enables us to see some things that we would not see if the object was, in nature, as large as it appears to our eye in the microscope. A small portion of muscle can, in a few minutes, be so prepared that a medium microscopic power will exhibit, with great distinctness, the delicate transversal striation of its fibers; while by vision only, we would probably not get any idea of this beautiful structure, if the object were, in nature, as large as it seems in the microscope.

On the other hand, however, even this circumstance, that microscopic observation has to be made under transparent illumination of the object, must be regarded as one of the greatest defects of microscopic vision, because this manner of seeing is so unusual and unnatural that it misleads and confuses our perception of what is seen ; and even the most experienced and trained microscopist cannot justly claim to have overcome the difficulty of properly discerning what he sees. As an illustration, an incident that happened

during my residence in Berlin, may be mentioned: A friend engaged in the special study of *Pleurosigma angulatum*, convinced me that he had correctly solved certain questions, and, finally, he published, as the result of his researches, that "this beautiful shell consists of a very thin and colorless membrane, covered, on both sides, with hemispherical bodies, which can be removed from the membrane." The publication was accompanied by a photograph of a certain *P. angulatum* shell, showing it partly deprived of the little hemispheres, and the membrane exposed, on which could yet be seen very faint impressions made by the hemispheres that had been removed. A few of the little hemispheres, however, could yet be seen, irregularly distributed over the denuded membrane, showing full color; and more of them, that had been washed off, were seen a little distance away from the shell. The rest, of course, were gone and lost forever. This illustration is the more interesting and striking, because the beautiful appearance of this diatom, as well as micro-photography, were quite new at that time.

Too late to prevent the publication, I found out, by accident, something that overturned the whole theory of my esteemed and scholastic friend. To be sure of it, I went immediately to see him; asked him for the original of the photograph, and, to his utter astonishment, then and there treated the very same shell that he had selected for his photograph, and restored to it all the hemispheres that it had at first.

After having noted the advantage and disadvantage of transparent illumination, respecting the understanding of what is seen by it, it must be admitted that, regardless of these questions, there is one circumstance which makes transparent illumination indispensable to the microscope; and this is the lack of light. Indeed, the microscope could never have arisen to any special usefulness, if objects could not be prepared to allow of transparent illumination, for the comparatively very small amount of the reflected light of almost all objects, which is only just sufficient in ordinary vision, proves to be quite insufficient in the microscope, even under moderate amplification. In fact, the adaptation of transparent illumination was one of the earliest improvements in microscopic observations, and opened the way to increase of magnification and improvement of the lenses.

Great as is the increase of light in the transparent illumination as compared with the ordinary reflected light of common objects, it fully satisfies us only in the use of the so-called low powers, when the medium powers begin to make a lack of light apparent. This fact, which from habit is scarcely noticed by the experienced microscopist, is strikingly apparent in the disappointment of a person, who, after having just had his first glance into a microscope through a low power objective, (say a one-inch), with plenty of light, then looks into it again after the power is changed to a quarter-inch. Ask him what he thinks of it, and in nine cases out of ten he will complain that there is not so much light as there was before—that it is not so brilliant. But he will break down completely if the objective is changed again to one of our modern triumphant high powers, say a sixteenth, and you will hardly convince him of the usefulness of this objective.

It takes a long time and much persistent practice to become familiar with working in the dark, and so to realize the full value of the use of such a power.

At all periods in the history of the microscope, constant efforts have been made to retrieve the loss of light on high powers; but after all it seems as if the proper manner of artificially increasing the light, whether it be by means of the intensity of the source of the light itself, or by means of optical apparatus, has not yet been developed. The experienced microscopist in his ordinary work finds it best, when using high powers, to avoid all artificial strengthening of the light that is used for the lowest powers; and he prefers, even for as high a power as a one-sixteenth, the ordinary diffused daylight. Not because he finds this light all he desires or needs, but because all the known methods of increasing light fail to increase the power of perception: on the contrary, they injure it. To avoid being misunderstood, it may be said that such work as resolving diatoms is not regarded here as ordinary work.

When the French optician, Chevalier, first acquired the idea that the microscope might be improved, as the telescope had been long before, by making the objective "achromatic," he certainly had in mind that, on this principle, a larger diameter could be given to the lenses; thus obtaining more light, which was greatly needed, espec-

ially for the higher powers of the old non-achromatic microscope. He naturally expected that the unpleasantly dark-looking field would then appear more like daylight. But in this he was rather disappointed, for the new objective, although bringing out a considerably better image of the object, left the field nearly as dark as it was with the old lenses. This fact soon led to the opinion that the great improvement of the image, as obtained by the achromatic lens, was owing almost exclusively to the correction of the aberrations of the same, until it was discovered that if the new achromatic objective was diaphragmed down to the diameter of the old non-achromatic one, the image, instead of being improved in distinctness of outline and markings, as compared with the non-achromatic, was really more rough and less distinct, contrary to anticipation, from the fact that the part cut off was the one of less perfect correction. It seemed then to be established that the increase of aperture of the objective had the effect of improving the distinctness of the image in a considerably higher degree than of increasing the light of the field; and this fact was soon explained thus: That the increase of the distinctness of the image is mostly due to the more and more inclining rays issuing from the object, and very little to the increased amount of light.

We may be assisted in the comprehension of a part of this subject by a consideration of some of the corresponding circumstances of observation with an astronomical telescope. In the heavens there are objects, the rays from which, on account of the distance of the source, can be considered parallel, even those entering the diametrical opposite extremities of the largest objective; hence we have here none of the inclination of the rays of the microscope objective.

When the moon is a day or two over the first quarter, with a four-inch telescope and a power of about two hundred diameters, the large crater, Plato, appears perfectly clear and distinct, and under sufficient light, also, to make us feel confident we see all on it that it has to exhibit; yet several smaller craters are seen very clearly with a larger telescope on this spot.

A microscopic analogy to this is *Pleurosigma angulatum* when looked at with an objective of large angular aperture, showing with

beautiful distinctness the hexagons, while even the best corrected small aperture objective shows the surface of this diatom perfectly smooth as if this was the only true structure of it.

The planet Venus, especially when in favorable position, always troubles the observer, even if his telescope is of the best class, because she has too much light. She is too brilliant, and this excess of light injures the distinctness of the outlines and clearness of the surface. But a larger telescope, if a good one, although the amount of light in it is increased, in the proportion of the square of the diameter of its object-glass, will not at all add to this indistinctness, but correspondingly reduces this error.

Rigel, also, the most brilliant star of the bright constellation Orion, will hardly be separated from its seventh magnitude companion with a small telescope; that is, the small star cannot be made visible by the side of the large one, not because they are too close for the instrument, nor because the small one is too faint; but it is because Rigel is too brilliant—has too much light and overshines its small companion. And this difficulty is quite common in observations of the stars.

Strange as it appears, the only method of separating such double stars is by the use of a telescope with a larger objective; that is, one that gives more light.

Summarizing these examples, we note from the first, that of the moon crater Plato, that for "resolution" of fine marked objects, such as diatoms or the central spot of Plato, inclined or strongly refracted rays are *not* necessarily required, but a sufficient amount of light only.

The second example, that of the planet Venus, shows that the intensity of the light issusing from the object cannot help to improve the clearness and distinctness of the image; and the double star example makes it evident that the so-called resolving power, as well as the definition, depends on the quantity which is gathered of the light radiating from the object.

We thus learn that we have to distinguish between quantity and intensity of light, much as we do in studying electricity. With a sufficient quantity of light we obtain those effects known as definition and resolution, while the intensity of the light issuing from the

object seems to have no part in this ; but under certain circumstances this rather injures it. The examples of celestial objects show that if the intensity of the light of the object is too great, the injurious effect of it can be reduced, perhaps completely removed or neutralized, by a proportionate increase of quantity; and, as a consequence of this, if the intensity of an object is too great proportionately to the quantity of light that the objective is capable of taking in, a corresponding decrease of the same must improve the definition and resolving power. There is a certain harmony in the proportion of both intensity and quantity of light. If we could in some way reduce the intensity of the light of Rigel, a much smaller telescope would show its little companion; and the same result would doubtless be obtained if the companion were as bright a star as the main one. On the other hand, the intensity of such a pair of bright stars, too great to be separated by a small telescope, will not be an impediment to the separation of the two stars, but will rather help it, if the telescope is only large enough so that the quantity of light taken by it is in harmony with the intensity of the light of the object. Indeed, if from this view a comparison of a number of suitable different double stars is made, to determine on each one the results in regard to their separation, obtained with telescopes of different aperture, it will sustain the correctness of the theory,. that for the best resolution of such objects, a proper harmony of both intensity and quantity of light is required. Of course we cannot insist upon a sharp line being drawn as to what would be the exact proportion for this harmony. There may be several circumstances that will effect it, such as the peculiarity of the eyes, etc. But we will probably at first have to be satisfied with simply the statement of the correctness of the theory and the leading results of practical experience.

Having developed this theory of harmonic proportion of quantity and intensity of light with celestial objects, we have now to investigate if, or how far, this theory is applicable to microscopic observation. Here we, at first, meet with one difficulty, which we do not have on celestial objects. While the latter appear to us as light objects on a dark ground, microsopic observation is based upon transparent illumination, as mentioned at the beginning. To

be able to compare this illumination of objects with that of the sky, it may be necessary to make ourselves familiar with the character of it. If we look into the tube of a microscope, with the eye-piece removed, but with a medium-power objective, say a quarter-inch, and the mirror standing "central," we notice in the center of the objective a small image of the mirror, while all the rest of the aperture appears dark. We can still reduce the size of this image by removing the mirror farther away from the objective, and increase the size by bringing it nearer. We find that, wherever we place the microscope, if in a room close to a window, so that the light can fall upon the mirror, or if far away from it, the image of the mirror will always keep its size and place in the center of the objective. Presuming that the light falling upon the mirror is sky-light, the rays coming from each point of the sky can be considered as parallel rays, and, if the mirror is a plane one, all the rays that its entire surface or aperture gathers from each point of the sky, will be reflected by it in one certain direction. If the direction of these reflected rays of one point of the sky is toward the objective, only that small portion of them which enters the objective in the very central part of it will aid in the formation of the image seen through the body in the center of the objective; for all other parts of the aperture of the latter, to direct rays passing through them, upwards along the body towards the eye, would have to enter the objective in the exact direction as if they came from the focus of the objective. But now, as the area of the source of light is very large, parallel rays of light will be sent out by the mirror in all directions within a corresponding limit, and, consequently, presuming that the mirror is suitably directed, a very small portion of each of these pencils will pass through that part of the aperture of the objective which, in regard to the focus of the latter, corresponds with the direction of the rays, if the said light-pencil, with one of its parts, hits the objective at that part. These pencils, or small portions of pencils, are, as to the direction of them, limited by the outline of the mirror. We see now how the little image of the mirror is formed in the center of the objective; a very small portion of parallel rays, coming within a limit described by the outline of the mirror from each point of the sky, and reflected by the mirror,

cross at the focal point of the objective, and pass through the latter at a certain corresponding part of the same. If, now, the mirror is a concave one, instead of plane, then the light rays, coming from each point of the light source, will be converging towards the objective; that is, they will now form a cone, instead of a parallel pencil, and, because they are not different in their directions, a larger portion of them will pass through the objective, and aid in the formation of the little image.

If the distance of the objective from the mirror is such that its focus will just coincide with that of the objective, then the maximum will be reached as to the amount of light by which the little image is formed. In this case, an image of the source of light, be this the flame of a lamp or a window, or even an indefinite part of the sky-light, is formed by the mirror right in the focal plane of the objective; and the size of it is proportional to the focal length of the mirror, and need not be larger than to cover completely the whole field of the eye-piece; and the "field" which we see in the eye-piece is nothing else than a *part* of this image of the light source, within which, at the same time, the image of the object appears, because the object is in the same plane with the mirror image of the light source, and, therefore, both together must form a mutual image at the eye-piece.

When a very low-power objective is used, such as a four-inch or a five-inch, we have some trouble to get the field equally illuminated; and, on changing the direction of the mirror, we see a somewhat indistinct image of the light source, the window, or the flame of the lamp, moving over the field; but we find that none of the light parts of this image are large enough to cover the whole field. The image of the light source, formed by the mirror at the plane of the object, is too small for so low a power. The focal distance of the mirror would have to be proportionally longer, to form an image large enough for so low a power.

It may be well to mention here that, not infrequently, the mistake is made, that, with the concave mirror of the microscope so adjusted that its focus coincides with that of the objective, *all* the light reflected by it crosses at one point, namely, at the focus of the objective; and that the mirror must be brought a little nearer to, or

farther away from, the object, to illuminate the whole of it. This is not correct. Only that light which comes from *one point* of the light source will meet or cross at one point, only, in the focal plane; but the whole surface of the light source is represented by a corresponding *image*.

Returning to the little image of the mirror, which we notice when looking into the body of the microscope, with the eye-piece removed, it may be asked, how is it we see only the central part of the one-fourth inch objective illuminated by the image of the mirror, while the outer zone, which represents a considerable area, appears dark? This is because the mirror can send its light through only so large an angular part of the aperture of the objective as is described by the extreme outside rays of the mirror, which is much less than the angular aperture of the objective; and, therefore, the surplus of the latter is left dark. The little image of the mirror which is seen in the center of the objective, indicates that part of the objective which is in direct action to form the image at the eye-piece. If the mirror is moved to one side, its image will follow only in the opposite direction. For the use of oblique illumination, we can always tell which part of the objective is brought in action by looking down the body toward the objective, and seeing what place the mirror-image takes upon the aperture. On testing the performance of a modern wide-angled objective, say of about 130° crown glass angle, the expert, before forming his opinion, by looking at the mirror-image as described above, should insure himself of having reached the extremity of the aperture. It requires some extraordinary illuminating contrivances to reach the extreme limit of the aperture of an objective of so wide an angle, and, in giving an opinion of what can be done with an objective, it would be useful to state under about what angle of obliquity of illumination the examination has been made; for just the extreme part of the aperture may be, or ought to be, the most valuable part of the objective, and, therefore, the opinion should refer mostly to that part, and the expert should be certain to have reached it with his illuminating apparatus.

We have now seen that the ordinary concave mirror, as illuminator of the microscope, can send its light through only a part of an objective, even of as moderate an angle as an ordinary one-fourth,

while it leaves in the dark the considerable remainder, which is by far the greatest portion on the wide-angled objectives. From this it may, at first, seem that such objectives, if the mirror is in central position, and no additional apparatus is used, would perform just as well, and not any better, than if it were so small an aperture that it could be filled out at one time by the light of the mirror. But this is not so. So great a part of the objective as is indicated by the image of the mirror seen in the center of the objective, is forming an image of the transparent illuminated object, while the rest of the objective relates to the object, as if the latter were opaque, and on a dark ground.

That this is so, can be made apparent, if that part of the objective which is not reached by the direct rays of the mirror, is cut off by a diaphragm. This will considerably reduce the resolving power of the objective. Also while this outer part of the objective appears to be dark, it will, if a suitable object, say a preparation of diatoms, is placed in the focal plane, exhibit that color which the object shows upon a dark ground. But great as is the influence of this outer dark-ground part of the objective in the formation of the details of the image, it does but very little to remedy the defect of light, so apparent especially on high powers.

Great efforts have been made at all periods of microscope history, to find the proper means of making the object appear more bright and clear, or in other words, to find a suitable way of compensating the great loss of light caused by amplification; and we should keep in mind that the light is inversely proportional to the magnifying power.

The only way that has yet been found of increasing the light is to condense the light reflected by the mirror by means of lenses or reflectors. The effect of the condenser is familiar to us: It greatly increases the brightness of the field and of the object. But, nevertheless, we know that the real advantage that this manner of lighting can give to the better perception of the details of the object is very limited. We have learned by experience, that the highly magnified object will not stand even that degree of brightness of illumination given by the condenser which the unaided eye is used to, and seems to require necessarily.

The reduction of light caused by amplification is a reduction of its intensity; while the condenser, as well as the aperture of the objective, as we have seen by the examples of celestial objects, only increases the quantity of light. The action of the condenser is nothing else than the shortening of the focal length of the mirror, and consequently a shortening of the light-cone and an increasing of the angle of the same. This increased angle increases correspondingly that central part of the objective which is directly illuminated by the mirror light, and which is indicated by the little image seen through the body of the microscope. If the condenser, in addition to that of the mirror, has an angular aperture equal to that of the objective, then the whole aperture of the latter will be illuminated by direct light, and will, when seen through the body, with the eye-piece removed, appear in equally brilliant light. The brightness of the field and the object, too, will then have reached its maximum. But, as said before, unfortunately the object has not gained in clearness of exhibition according to this increase of light, but in most cases has rather lost. It is the quantity of light which is increased by these means, while the immense amount of intensity lost by amplification does not receive any compensation in this way. To increase the intensity of the light of the object, the same will have to be illuminated by a strong light, but as much as possible limited in direction. Taken strictly, only that light falling upon the object in one direction will increase its intensity and not at all its quantity.

If we could only find a suitable way to accomplish this perfectly, we would, with it, open a new era to microscopic research, but in fact the accomplishment of this seems to be exceedingly difficult. A very intense light, perhaps best, the direct sunlight, will have to be thrown in one direction only upon that side of the object to be examined, to be reflected by the latter. The usual method of using direct sunlight does not fulfill this condition at all, for the light enters the objective directly, and the very little advantage obtained in this manner should be attributed to the contrast of the intense sunlight with the lack of intensity of the reflected light of the object. Perhaps an exceedingly small mirror or reflecting prism placed behind the back lens of the objective, in its center, in

such a manner that a beam of direct sunlight, or some very intense artificial light, entering the objective through a side opening and falling upon the reflector, will be directed through the central part of the objective. But, as said, the reflector would have to be exceedingly small to reduce the quantity of the sunlight to a minimum.